# PHOTOGRAMMETRIC ANALYSIS OF GRAND CANYON BEACHES

**For:** Bureau of Reclamation
Arizona Projects Office
Phoenix, Arizona

**By:** Gary Robertson & Assoc., Inc.
2901 N 78 St. Suite 200
Scottsdale, AZ. 85259

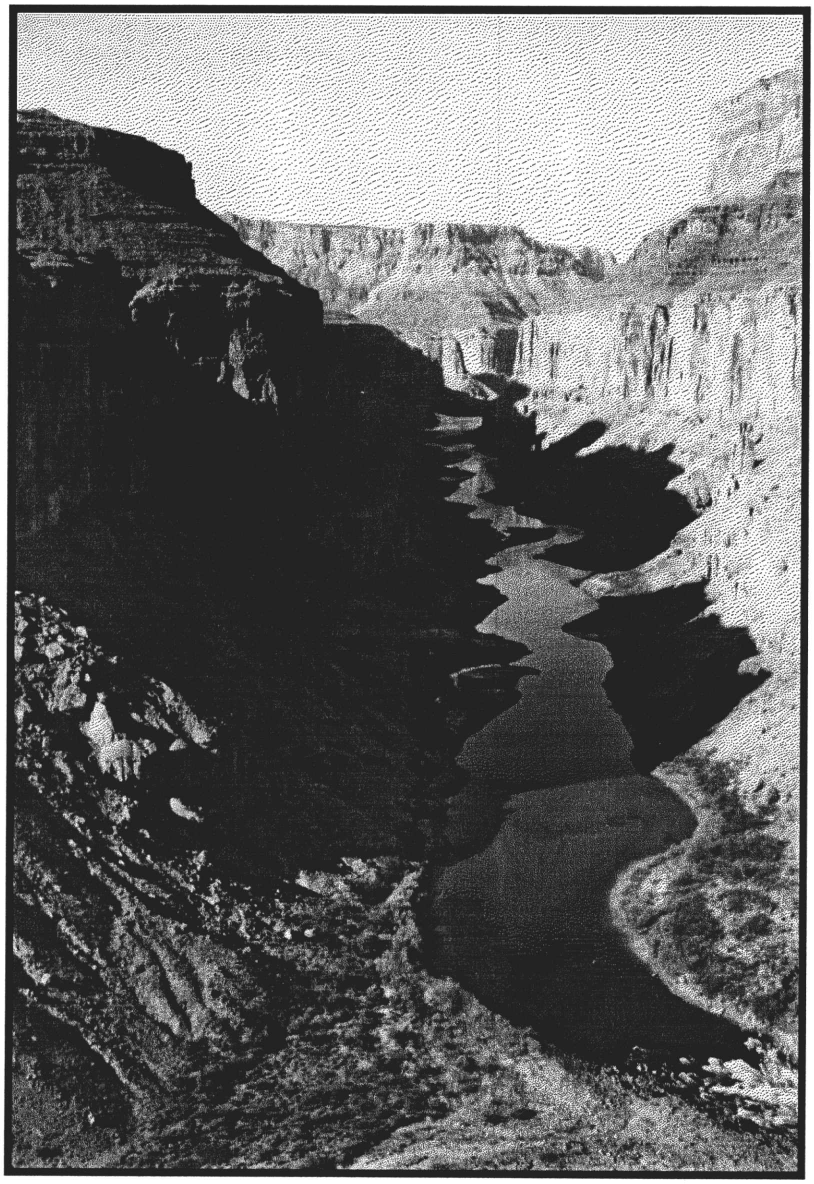


**TABLE OF CONTENTS**

## LIST OF FIGURES

## LIST OF TABLES

# 1.0 INTRODUCTION

The Arizona Projects Office (APO) was requested in September of 1990 to assist in the evaluation of beach loss and gain in the Grand Canyon. In order to conclude and formalize the subject studies, the Bureau of Reclamation's Upper Colorado Regional Office has requested that a final report be prepared and submitted by APO which details the results and findings associated with the analysis.

APO requested that Gary Robertson & Associates Inc. (GRA) prepare a comprehensive report. This report deals with the data extraction techniques, mathematical discussion, analysis and interpretation of the data and recommendations for further photogrammetric implementations.

## 1.1 Background

The close range/terrestrial photogrammetric task was in support of the Glen Canyon Environmental Studies research flows from the Glen Canyon Dam.

The photogrammetric analysis would be used to support the ground survey program and provide a larger sample of beaches for evaluation. There was a total of 17 epochs of reduced research flows during the evaluation of the beaches in the Grand Canyon. An epoch represents a 3 day window when flows from Glen Canyon Dam are reduced so that the study beaches would be above water. The research flows cost the Bureau of Reclamation approximately $250,000 each epoch and were tightly scheduled.

The photogrammetric task was to be accomplished by low level helicopter flights during the research flows. The photogrammetry was to yield mapping accuracies in the realm of 10 cm.

## 1.2 OVERVIEW OF PHOTOGRAMMETRY

Basically photogrammetry is the science and technology of obtaining reliable information about physical objects through processes of recording, measuring, and interpreting photographic images and patterns of electromagnetic radiant energy and other phenomenon.

Photogrammetry can be divided into several areas of interest, aerial applications used in the production of topographic maps and surveys, a remote sensing process which applies to producing conventional maps, and interpretation in the areas of agriculture, forestry, geography, and others.

Close range photogrammetry, also referred to as terrestrial photogrammetry, is applied to measuring physical objects, from or near the ground at fairly close taking distances.

Close range photogrammetry is unique in that it can be applied to every area of science and engineering, and works very well with conventional measuring methods. Areas of application in which Gary Robertson & Assoc. Inc. are applying close range photogrammetric principles include, Aeronautical engineering, Architecture, Archaeology, Civil engineering, Marine engineering Mining, Geotechnical and Medical applications.

In recent years growing interest has been expressed in the need for obtaining fast, accurate and reliable measurements of scientific and engineering structures. Close range photogrammetry has expanded rapidly over the last ten years due to the power and low cost of computer hardware.

During the early nineteen eighties close range photogrammetry was selected as one of the primary sources of quality assurance for the new generation aircraft and ships. In 1982 Northrop corporation recognizing the benefits of close range photogrammetry wanted to fully automate the procedure rather than using human operator measurement tasks. GRAI and Northrop developed the first fully automated close range photogrammetric system. The F18 tooling was verified and life cycle test can be achieved to an accuracy of 1:350,000 of the dimension of the object. The photogrammetry procedures and the software used for this study are the same that were tested and bench-marked for the USN and USAF.

A few major advantages of using the photogrammetric techniques include:

1. Photographs take little time to produce no matter how complicated the shape of the object. This method is ideal for studies of quality control in manufacturing where speed reduces interruption time.

2. Objects to be photographed need not be entered or touched. Thus objects can be measured whether they are burning, glowing, exploding, radioactive or in situations where conventional measuring techniques would alter or damage the shape of the object.

3. Objects can be photographed whether they are static or dynamic using exposure rates from one frame per second to several hundred frames per second.

4. Photogrammetric photographs have a high demonstrative capacity and a high information content. The objects photographed are shown objectively and in detail.

5. Photographs permit the revision and later checking of measurements. This is particularly true if certain details in the first measurement phase had been overlooked or seen later to be more important than first assumed.

6. Digital data is extracted from the photograph in a form suitable for computation, several image points to several thousand can be measured.

7. Photography and measurements are two separate operations. Therefore the mensuration phase can be conducted with the use of archived photographs some time later even years later.

8. Measurements are in three dimensions X,Y,Z and computed coordinates can be directly interfaced into CAD/CAM system.

9. Reliability, photogrammetric mensuration accuracies have been proven over existing conventional mensuration techniques.

## 2.0 COMPUTER SIMULATION OF A PHOTOGRAMMETRIC SURVEY

Due to the varying situations and applications that may be encountered in a close range photogrammetric survey, a computer simulation of the survey is an invaluable tool. In this case, the coordinates of a design surface are generated mathematically. By assuming the locations of the expected camera station coordinates and orientation parameters, the photo coordinates of a point are generated synthetically. In order to provide a realistic simulation, these synthetic photo coordinates are disturbed (usually by a random number generator). This has the effect of synthetically introducing random errors into the system that are expected to occur in practice.

By processing this data through the bundle adjustment program, various configurations of targeted points, camera station locations and control point information can be examined with respect to the achievable and expected accuracy. Since the initial targeted points were synthetically generated, all object point coordinates are fully known and absolutely accurate.

The following examples are computed for the 8.0 mile test beach. The exposure stations were located with various base distances. The image coordinates were randomly disturbed by a random number generator based on a uniform distribution, with the maximum error being +/- 10 um. This error is generally somewhat higher than is usually expected in practice. normally 6 um would be used for this type of measurement. The results of the analysis are shown in Tables 1.thru 4 and the simulation 70 mm image frames are shown in Figure1 and 2.

The accuracy of this system can be increased or decreased according to the specifications of any project. Moving the camera stations closer to the object will increase the accuracy, while possibly requiring more photographs to complete full coverage of the object. It should be noted that the accuracy has been distorted by more than the expected amount of a real survey in order to provide an upper bound to the anticipated accuracy.

The simulated data was verified by actual data taken of the 8.0 mile test beach with no compensation for lens distortions which will be explained in more detail in the next section.

A more simplistic approach is the base distance ratio method that describes accuracy relating solely from the focal length, camera base distance and distance to the subject.

This is expressed by the following:

B - base distance of cameras
ck - focal length of camera
dp - measurement accuracy
Y - distance from subject
DY - delta Y or expected error

$$B = \frac{Y^2 * dp}{CK * DY} \qquad Dy = \frac{Y^2}{b * ck} * dp$$

**Example**: The following parameters are considered:

Y distance 350 meters,
Focal length 150.0 mm
Camera base 94 meters
Measuring accuracy 10 microns

These parameters would produce an error of **87.0 mm.**. The simulated data using distributed control points provided an RMS of **55.0 mm.** in Z

NOTE: As you can see from these examples there are differences using a base distance formula and a true simulation program. This method compounded by incorrect procedures of relating to lens distortion makes for an unreliable procedure to determine the overall accuracies of the photogrammetric design.

Before any simulation can be undertaken we must first determine the accuracy requirements, the photographic environment and what camera system is to be used.

The GCES had determined an accuracy requirement for the beaches at 10 cm in elevation. The photographic acquisition was to be from a helicopter. The format selected was 70 mm which provided for a square footprint of the beaches.

The altitude or camera distance is determined by the accuracy required and the size of the area to be mapped. The shutter speed and airspeed effects image motion. Therefore the camera distance of 365 meters with the nominal focal length of 150mm would provide the necessary accuracy and the photo scale would allow for airspeeds of 30 Knots without any noticeable image motion effects.

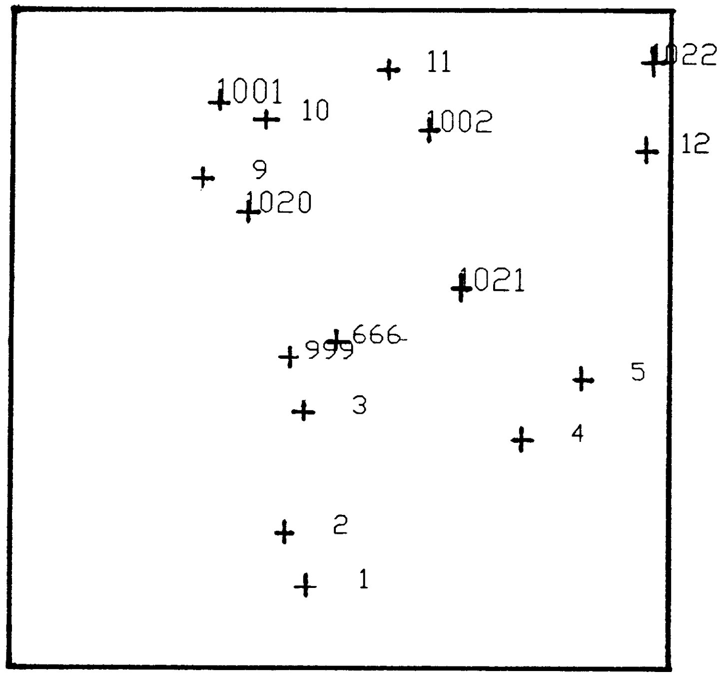



**Figure 1.**

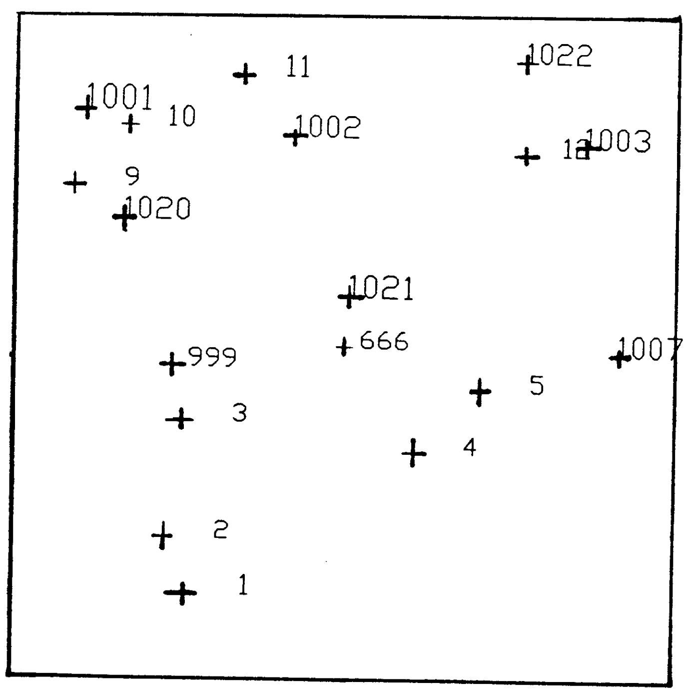



**Figure 2.**

## Simulation of 8.0 mile Beach

### Table 1

Camera base of 94.0 meters with 10 microns disturbed data

```
***************************************************************************************
*                                                                                     *
*    < SPECIAL - TERRESTRIAL - APPLICATIONS - PROGRAM & CAMERA-CALIBRATION >          *
*                                                                                     *
***************************************************************************************

  JOB  :  BEACH 8.0R SIM/10 micron

NUMBER OF CONTROL POINTS      =       15

STANDARD ERROR OF UNIT WEIGHT =     .005

     C                          150.400                 +      .000          (FIXED)

     XC                        1036.837                 ∓      .145

     YC                         959.974                 ∓      .136

     ZC                         445.004                 ∓      .041

     OMEGA      (+)   8 DEG  17 MIN   5.52 SEC          ∓   83.20 SEC

     PHI        (+)   6 DEG  38 MIN   2.02 SEC          ∓   85.76 SEC

     KAPPA      (+)  89 DEG  59 MIN  49.52 SEC          ∓   24.69 SEC

     XC                        1021.819                 ∓      .147

     YC                        1052.676                 ∓      .169

     ZC                         443.981                 ∓      .034

     OMEGA      (-)   2 DEG  41 MIN  48.32 SEC          ∓  103.11 SEC

     PHI        (+)   4 DEG  28 MIN  12.01 SEC          ∓   87.70 SEC

     KAPPA      (+)  90 DEG  53 MIN  18.10 SEC          ∓   29.22 SEC
```

(PHOTO 2)

TRANSFORMED COORDINATES - RESIDUAL PARALLAXES ( DISTORTION PARAMETERS : NONE )

| (POINT) | (X) | (Y) | (Z) | (PX) | (PY) | (PZ) | (PP) |
|---|---|---|---|---|---|---|---|
| 1 | 1048.343 | 1004.458 | 95.189 | .001 | .000 | .000 | .001 |
| 2 | 1036.685 | 999.727 | 96.620 | .010 | .002 | .000 | .010 |
| 3 | 1011.657 | 1002.899 | 100.446 | .020 | .003 | -.001 | .020 |
| 4 | 1016.452 | 1051.985 | 95.705 | -.016 | -.003 | .000 | .016 |
| 5 | 1002.710 | 1065.662 | 96.423 | -.003 | -.001 | .000 | .003 |
| 9 | 964.281 | 979.920 | 113.763 | -.007 | -.001 | .002 | .007 |
| 10 | 952.973 | 991.993 | 120.197 | .030 | .005 | -.007 | .031 |
| 11 | 944.026 | 1015.884 | 128.708 | -.019 | -.003 | .005 | .020 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 12 | 956.867 | 1072.173 | 122.551 | .017 | .003 | -.003 | .017 |
| 999 | 1000.001 | 999.999 | 100.050 | -.024 | -.004 | .002 | .024 |
| 1001 | 949.334 | 982.667 | 118.284 | -.009 | -.001 | .002 | .009 |
| 1002 | 954.336 | 1025.788 | 121.549 | -.019 | -.003 | .004 | .020 |
| 1020 | 970.048 | 989.757 | 107.894 | -.000 | .000 | .000 | .000 |
| 1021 | 984.242 | 1037.187 | 101.639 | .003 | .001 | -.000 | .003 |
| 1022 | 940.208 | 1071.250 | 130.771 | .017 | .003 | -.004 | .018 |
| R.M.S. CONTROL POINTS............................... | | | | .016 | .003 | .003 | .016 |

CHECK POINT DISCREPANCIES ( DISTORTION PARAMETERS : NONE )

| (POINT) | (DX) | (DY) | (DZ) |
|---|---|---|---|
| 1 | -.011 | -.000 | .031 |
| 2 | -.002 | .003 | -.043 |
| 3 | -.003 | -.005 | -.047 |
| 4 | -.002 | .010 | .045 |
| 5 | -.002 | .007 | .004 |
| 9 | .008 | -.011 | .010 |
| 10 | -.034 | .010 | -.117 |
| 11 | .012 | .007 | .091 |
| 12 | -.010 | .003 | -.040 |
| 999 | .001 | -.001 | .050 |
| 1001 | -.001 | -.012 | -.035 |
| 1002 | .021 | -.011 | .062 |
| 1020 | -.002 | -.002 | .013 |
| 1021 | .028 | -.017 | .053 |
| 1022 | -.011 | .016 | -.058 |
| (R.M.S) | .014 | .009 | .055 |

## Table 2

Camera base of 85.0 meters with outer control.

```
*******************************************************************************************
*     < SPECIAL - TERRESTRIAL - APPLICATIONS - PROGRAM & CAMERA-CALIBRATION >             *
*                                                                                         *
*******************************************************************************************

   JOB  :  BEACH 8.0R SIM/10 micron

  NUMBER OF CONTROL POINTS      =        6

  STANDARD ERROR OF UNIT WEIGHT =     .003

       XC                        1022.381              +      .281

       YC                        1052.784              ∓      .178

       ZC                         444.049              ∓      .053

       OMEGA        (-)   2 DEG  43 MIN   2.19 SEC     ∓  107.46 SEC

       PHI          (+)   4 DEG  33 MIN  42.09 SEC     ∓  164.25 SEC

       KAPPA        (+)  90 DEG  54 MIN  17.42 SEC     ∓   53.78 SEC
                                                                            (PHOTO 1)
```

| | | | |
|---|---|---|---|
| XC | 1010.875 | ∓ | .287 |
| YC | 1137.932 | ∓ | .223 |
| ZC | 442.027 | ∓ | .077 |

| | | | | | | |
|---|---|---|---|---|---|---|
| OMEGA | (-) | 4 DEG | 56 MIN | 13.05 SEC | ∓ | 134.59 SEC |
| PHI | (+) | 4 DEG | 28 MIN | 45.82 SEC | ∓ | 169.97 SEC |
| KAPPA | (+) | 91 DEG | 47 MIN | 46.32 SEC | ∓ | 60.13 SEC |

(PHOTO 2)

TRANSFORMED COORDINATES - RESIDUAL PARALLAXES ( DISTORTION PARAMETERS : NONE )

| (POINT) | (X) | (Y) | (Z) | (PX) | (PY) | (PZ) | (PP) |
|---|---|---|---|---|---|---|---|
| 4 | 1016.453 | 1051.975 | 95.631 | .012 | .002 | -.000 | .012 |
| 5 | 1002.715 | 1065.652 | 96.459 | -.016 | -.002 | .001 | .016 |
| 12 | 956.876 | 1072.165 | 122.598 | -.003 | -.000 | .001 | .003 |
| 1003 | 954.646 | 1084.078 | 120.934 | .013 | .002 | -.002 | .013 |
| 1007 | 994.215 | 1094.745 | 98.060 | -.000 | .000 | .000 | .000 |
| 1022 | 940.226 | 1071.241 | 130.853 | -.005 | -.001 | .001 | .005 |
| R.M.S. CONTROL POINTS............................... | | | | .010 | .001 | .001 | .010 |

CHECK POINT DISCREPANCIES ( DISTORTION PARAMETERS : NONE )

| (POINT) | (DX) | (DY) | (DZ) |
|---|---|---|---|
| 4 | -.001 | -.000 | -.029 |
| 5 | .003 | -.003 | .040 |
| 12 | -.001 | -.005 | .007 |
| 1003 | -.009 | -.004 | -.050 |
| 1007 | .000 | .005 | .010 |
| 1022 | .007 | .007 | .024 |
| (R.M.S) | .005 | .005 | .031 |

# Table 3

Camera base of 50 meters at 10 microns.

```
******************************************************************************************
*                                                                                        *
*    < SPECIAL - TERRESTRIAL - APPLICATIONS - PROGRAM & CAMERA-CALIBRATION >             *
*                                                                                        *
******************************************************************************************
```

JOB : BEACH 8.0R SIM/10 microns

NUMBER OF CONTROL POINTS = 16

STANDARD ERROR OF UNIT WEIGHT = .005

| | | | | |
|---|---|---|---|---|
| XC | | 1029.819 | ± | .132 |
| YC | | 999.986 | ± | .116 |
| ZC | | 444.002 | ± | .026 |
| OMEGA | (+) | 8 DEG 16 MIN 57.46 SEC | ± | 70.40 SEC |
| PHI | (+) | 6 DEG 37 MIN 49.34 SEC | ± | 78.69 SEC |
| KAPPA | (+) | 90 DEG 0 MIN 1.04 SEC | ± | 21.33 SEC |

(PHOTO 1)

| | | | | |
|---|---|---|---|---|
| XC | | 1022.054 | ± | .146 |
| YC | | 1050.223 | ± | .147 |
| ZC | | 443.953 | ± | .027 |
| OMEGA | (-) | 2 DEG 44 MIN 15.79 SEC | ± | 89.11 SEC |
| PHI | (+) | 4 DEG 30 MIN 35.78 SEC | ± | 87.51 SEC |
| KAPPA | (+) | 90 DEG 54 MIN 25.96 SEC | ± | 25.43 SEC |

(PHOTO 2)

TRANSFORMED COORDINATES - RESIDUAL PARALLAXES ( DISTORTION PARAMETERS : NONE )

| (POINT) | (X) | (Y) | (Z) | (PX) | (PY) | (PZ) | (PP) |
|---|---|---|---|---|---|---|---|
| 1 | 1048.350 | 1004.459 | 95.298 | -.022 | -.003 | -.001 | .022 |
| 2 | 1036.694 | 999.722 | 96.800 | -.015 | -.002 | -.000 | .015 |
| 3 | 1011.664 | 1002.894 | 100.472 | .008 | .001 | -.000 | .009 |
| 4 | 1016.445 | 1051.987 | 95.699 | -.002 | -.000 | .000 | .002 |
| 5 | 1002.701 | 1065.670 | 96.361 | .000 | .000 | .000 | .000 |
| 10 | 953.028 | 991.987 | 120.377 | .008 | .001 | -.002 | .008 |
| 11 | 944.074 | 1015.889 | 128.857 | -.040 | -.006 | .011 | .042 |
| 12 | 956.877 | 1072.165 | 122.556 | -.004 | -.001 | .001 | .004 |
| 999 | 999.986 | 1000.003 | 100.031 | .001 | .000 | .000 | .001 |
| 1001 | 949.290 | 982.656 | 118.140 | .007 | .001 | -.002 | .007 |
| 1002 | 954.295 | 1025.806 | 121.421 | -.005 | -.001 | .001 | .005 |
| 1003 | 954.636 | 1084.094 | 120.913 | .025 | .004 | -.005 | .026 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 1007 | 994.216 | 1094.721 | 98.168 | .012 | .002 | -.001 | .012 |
| 1020 | 970.021 | 989.743 | 107.698 | .007 | .001 | -.001 | .007 |
| 1021 | 984.192 | 1037.217 | 101.405 | .033 | .005 | -.004 | .034 |
| 1022 | 940.243 | 1071.224 | 130.855 | -.008 | -.001 | .002 | .009 |
| R.M.S. CONTROL POINTS................................ | | | | .017 | .003 | .003 | .017 |

CHECK POINT DISCREPANCIES ( DISTORTION PARAMETERS : NONE )

| (POINT) | (DX) | (DY) | (DZ) |
|---|---|---|---|
| 1 | -.004 | .001 | .140 |
| 2 | .007 | -.002 | .137 |
| 3 | .004 | -.010 | -.021 |
| 4 | -.009 | .012 | .039 |
| 5 | -.011 | .015 | -.058 |
| 10 | .021 | .004 | .063 |
| 11 | .060 | .012 | .240 |
| 12 | .000 | -.005 | -.035 |
| 999 | -.014 | .003 | .031 |
| 1001 | -.045 | -.023 | -.179 |
| 1002 | -.020 | .007 | -.066 |
| 1003 | -.019 | .012 | -.071 |
| 1007 | .001 | -.019 | .118 |
| 1020 | -.029 | -.016 | -.183 |
| 1021 | -.022 | .013 | -.181 |
| 1022 | .024 | -.010 | .026 |
| (R.M.S) | .024 | .012 | .120 |

## Table 4

Camera base of 50 meters with 6 micron data

```
****************************************************************************************
*                                                                                      *
*    < SPECIAL - TERRESTRIAL - APPLICATIONS - PROGRAM & CAMERA-CALIBRATION >           *
*                                                                                      *
****************************************************************************************
```

JOB : BEACH 8.0R SIM/6 micron

NUMBER OF CONTROL POINTS = 16

STANDARD ERROR OF UNIT WEIGHT = .003

| | | | | | | |
|---|---|---|---|---|---|---|
| XC | | 1029.887 | | | ∓ | .080 |
| YC | | 999.988 | | | ∓ | .070 |
| ZC | | 444.996 | | | ∓ | .015 |
| OMEGA | (+) | 8 DEG | 16 MIN | 56.44 SEC | ∓ | 42.58 SEC |
| PHI | (+) | 6 DEG | 38 MIN | 29.74 SEC | ∓ | 47.56 SEC |
| KAPPA | (+) | 89 DEG | 59 MIN | 59.98 SEC | ∓ | 12.90 SEC |

PHOTO 1)

| | | | |
|---|---|---|---|
| XC | 1022.031 | ∓ | .089 |
| YC | 1050.136 | ∓ | .090 |
| ZC | 443.966 | ∓ | .017 |
| OMEGA | (-) 2 DEG 43 MIN 22.95 SEC | ∓ | 54.58 SEC |
| PHI | (+) 4 DEG 30 MIN 20.80 SEC | ∓ | 53.61 SEC |
| KAPPA | (+) 90 DEG 54 MIN 16.40 SEC | ∓ | 15.58 SEC |

(PHOTO 2)

TRANSFORMED COORDINATES - RESIDUAL PARALLAXES ( DISTORTION PARAMETERS : NONE )

| (POINT) | (X) | (Y) | (Z) | (PX) | (PY) | (PZ) | (PP) |
|---|---|---|---|---|---|---|---|
| 1 | 1048.351 | 1004.459 | 95.252 | -.012 | -.002 | -.001 | .012 |
| 2 | 1036.692 | 999.722 | 96.740 | -.009 | -.001 | -.000 | .009 |
| 3 | 1011.663 | 1002.898 | 100.489 | .004 | .001 | -.000 | .004 |
| 4 | 1016.449 | 1051.981 | 95.698 | -.002 | -.000 | .000 | .002 |
| 5 | 1002.705 | 1065.665 | 96.377 | .001 | .000 | .000 | .001 |
| 10 | 953.020 | 991.986 | 120.354 | .005 | .001 | -.001 | .005 |
| 11 | 944.050 | 1015.884 | 128.762 | -.024 | -.004 | .006 | .025 |
| 12 | 956.877 | 1072.168 | 122.565 | -.003 | -.000 | .000 | .003 |
| 999 | 999.992 | 1000.002 | 100.016 | -.001 | -.000 | .000 | .001 |
| 1001 | 949.307 | 982.665 | 118.206 | .004 | .001 | -.001 | .004 |
| 1002 | 954.303 | 1025.803 | 121.446 | -.002 | -.000 | .001 | .003 |
| 1003 | 954.644 | 1084.089 | 120.945 | .016 | .002 | -.003 | .016 |
| 1007 | 994.215 | 1094.729 | 98.118 | .008 | .001 | -.000 | .008 |
| 1020 | 970.033 | 989.750 | 107.770 | .004 | .001 | -.001 | .004 |
| 1021 | 984.199 | 1037.212 | 101.467 | .021 | .003 | -.002 | .022 |
| 1022 | 940.234 | 1071.227 | 130.847 | -.006 | -.001 | .001 | .006 |
| R.M.S. CONTROL POINTS............................. | | | | .010 | .002 | .002 | .011 |

CHECK POINT DISCREPANCIES ( DISTORTION PARAMETERS : NONE )

| (POINT) | (DX) | (DY) | (DZ) |
|---|---|---|---|
| 1 | -.003 | .001 | .094 |
| 2 | .005 | -.002 | .077 |
| 3 | .003 | -.006 | -.004 |
| 4 | -.005 | .006 | .038 |
| 5 | -.007 | .010 | -.042 |
| 10 | .013 | .003 | .040 |
| 11 | .036 | .007 | .145 |
| 12 | -.000 | -.002 | -.026 |
| 999 | -.008 | .002 | .016 |
| 1001 | -.028 | -.014 | -.113 |
| 1002 | -.012 | .004 | -.041 |
| 1003 | -.011 | .007 | -.039 |
| 1007 | .000 | -.011 | .068 |
| 1020 | -.017 | -.009 | -.111 |
| 1021 | -.015 | .008 | -.119 |
| 1022 | .015 | -.007 | .018 |
| (R.M.S) | .015 | .007 | .075 |

## 3.0 CAMERA SYSTEMS

Several camera systems were considered for the test and photography of the beaches. It is important to note that photogrammetric accuracy is not based on film size but rather the photographic scale factor. Thus any format of camera can produce the desired accuracies based on comparable scale, but one needs to realistically consider the number of images required for extremely small format film.

For the photography of the beaches several cameras were considered. APO and GRA have the largest selection of close range cameras available in North America. In general for the type of photography such as "skid" photography in the canyon a small format camera such as 70mm should be used. This is based upon tests and over twelve years of helicopter photography of canyons and mountain faces. The subject of camera selection will be discussed further in the conclusion and recommendations.

1- The 70mm type of camera allows for easy hand held use

2- The need for direct magnified viewfinder for the camera

3- The operator can adjust for buffeting in the helicopter and quickly compensate during the photography.

4- Ease of film changing.

5- Small film magazines allow for various film types or speeds for different subjects and lighting conditions.

6- Availability of film in remote locations.

7- Square footprint of the image provides optimum coverage of the beaches especially for the photo control and targeting.

8- Sharp imagery

9- Ability of interchanging lenses.

**Larger cameras like the UMK/200 provide some problems.**

1- It is fixed to the helicopter

2- If during the photography the helicopter buffets or crabs no correction can be made requiring additional flight's over of the beach.

3- The footprint does not necessarily work very well with all the beaches.

4- Problems with loading the camera in most cases necessitate landing the helicopter in a sensitive area like the Grand Canyon or using up valuable time and fuel to fly to an area to unload. Loading the camera on the ground is due to safety reasons.

5- The large film magazines create problems in changing the film speeds. In the Grand Canyon the lighting changes almost for each beach.

6- If shorter lengths of film were loaded in the magazine you would have to consider the problems of reloading the camera.

7- If the footprint of the beaches are not favorable it provides serious problems for the survey photo control and targeting that would have to be placed in inaccessible sections of the canyon.

8- This can especially be applied to large format aerial cameras of 23cm. although some newer 23cm cameras are equipped with motion compensation the footprint would have to be considered.

An additional item that needs to be considered is the shutter speed of the camera. The UMK shutter speed is 1/400 of a second and most 70mm cameras provide for a shutter speed of 1/500 to 1/1000 of a second. For the altitude or the distance for this test and the airspeed flown 1/500 of a second is adequate for our work. We tested a high speed 70 mm camera in the canyon, the camera offered shutter speeds of 1/4000 of a second with frame rates of 1 thru 20 frames a second. Considering the film available at the time the lighting conditions in the canyon would not allow us to use more than 1/1000 of a second shutter speed. The problem with this type of camera is the lack of a direct magnified optical viewfinder, this created problems in the stereo overlap and alignment of the beaches.

The camera did provide for continuous frame rates up to 20 frames per second. This would create a lot of images, additional time would be required to select the appropriate frames. The 100 foot film reels are difficult to load versus the 12 frame magazine. In addition when loading the film a film changing bag or blanket is required to prevent light leaks. This basically is impossible due to flight safety, since everything has to be secured in the helicopter.To compound the problem 100 foot spools of 70 mm have to be special ordered. A case in point GRA had placed an order for 100 foot reels over 10,000 feet of film for anther project and it required nearly 90 days to receive the film direct from the factory.

## 4.0 CAMERA CALIBRATION

For any type of photogrammetric measurement an accurate calibration of the cameras must be known. All cameras used by APO and GRA for measurement and mapping have been calibrated. The basic calibration of focal length, offset for the lens principal point, radial and tangential distortion are known.

The cameras used in the GCES study were additionally calibrated on two occasions, November of 1990, and June 1991. This provided a check of consistencies on the lens used and to determine any deviations in the original calibration.

The camera system used for the majority of the GCES study was the Rollei 6006 Photogrammetric camera equipped with a reseau plate and 150mm lens. APO had constructed a calibration test field at the APO facility in Phoenix The system is very accurate and provides for an excellent lens calibration fixture.

The Rollei lens calibration proved to be within nominal distortions for this lens with over 100 microns of radial distortion balanced out to 25mm. It should be pointed out that there is confusion among the GCES support groups regarding radial distortion. The standard Gaussian distortion function does not involve a linear term. A linear term can be introduced by adjusting the calibrated principal distance by an arbitrary increment. This leads to a projectively equivalent distortion function or a balanced function. This forces the transformed function to assume the value of zero at a specified radial distance.

A new aerial 23cm mapping lens may show a Gaussian function of over 100 microns with a transformed function under 10 microns. The majority of 70mm German made lens show Gaussian function in excess of 250 to 325 microns. The transformed function should be considered.

## 5.0 Photogrammetric Evaluation of the 8.0 mile Test Beach

In May 1991 GRA suggested to APO that a test be undertaken of a beach in the GCES environmental study. The 8.0R mile beach was selected based on the access to the beach. GRA was responsible for the target placement, survey and survey computations. In addition we were to evaluate the photography to date for the beach and prepare the models for mapping.

The survey and targeting were undertaken in two field trips due to mis-communication with the GCES support people. The first day all survey data was collected with two Wild T-2000 theodolites and a Wild DI-2000 distance meter. The Wild instruments are high precision total stations.

For the second survey a Leitz set 3 total station was used. This is a second order instrument, the difference in resolution between systems was approximately **10 mm in X, Y and 25 mm in Z.** The differences are due to the superior leveling and axis collimation associated with the Wild equipment. All targets used in the photogrammetric solution were double tied from two stations with both faces of the instrument. to eliminate decentering errors. This provided for an accurate and reliable survey of the control points.

### 5.1 Tests that were made of the beach:

1: Set up the stereo models for the post survey epochs.

2: review the pre survey photographic epochs

3: test for accuracies real versus simulated

4: test data on a first and 3rd order instrument.

5: test for repeatability

6: test for resolution: for the ability to measure fine sand deposits under various lighting conditions.

7: Preparation of XYZ digital data of the beach

8: use of natural features for photogrammetric control

## 5.2 Results of Test

The post targeting and survey photography were measured on a Wild BC2 and Autometric Apps IV plotter. The last three epochs in the GCES study 6/29/91, 7/14/91, 7/29/91 were measured by the APPS IV plotter at the Bureau of Reclamation's Arizona project office.

The May photography was measured on a Wild BC2 analytical plotter The camera base distance was less than 75 meters and the model data was within 84 mm in elevation. The subsequent stereo models of the flight line contained image motion that caused parallax in the model space, this created errors in Z on some locations of the beach.

The images were tested for repeatability and were within 53 mm on the profiles taken. In addition eight random locations were chosen on the fine deposits on the beach and repeatedly read to test the ability of placing the floating point on the sand. The photography from February thru June 1991 was within 36 mm.

The stereo models of the 8.0 mile beach were analyzed back to October 1990. The film speeds due to either overcast conditions, heavy shadows required film speeds from ASA 400 to 6400. The photography at 3200 to 6400 ASA film speeds was extremely difficult to read with repeatability of the fine deposits at 300 mm to 500 mm. The altitudes flown had varied between the epochs and a percentage of the camera bases was small this made it difficult meet the required mapping accuracies.

The last three epochs were chosen for testing on the APO APPS IV. this machine is a third order instrument with a measuring accuracy of 10 microns. In addition this machine has less than acceptable optics and poor illumination compared to commercial mapping instruments. To measure the beaches properly APO had to prepare diapositives for the measurement phase.

The following is the residuals of the APPS model setup obtained on August 14, 1991.

6-29-91 (11 points)

| | X | Y | Z |
|---|---|---|---|
| RMS | 0.039 | 0.038 | 0.050 |

7-14-91 (14 points)

| | X | Y | Z |
|---|---|---|---|
| RMS | 0.046 | 0.065 | 0.079 |

7-29-91 (14points)

| | X | Y | Z |
|---|---|---|---|
| RMS | 0.046 | 0.044 | 0.060 |

The GRA simulation for this instrument was :

| RMS | X | Y | Z |
|---|---|---|---|
| | 0.014 | 0.019 | 0.055 |

As you can see the APO measured models compares very well with the simulation data. The models of all three epochs were then digitized by APO. The profiles sections were take at 1.2 meters in X and 1.5 meters in Y. Sample profile's are shown in Tables 5 and 6. contours or DTM can also be derived from this digital data.

**<u>NOTE</u>: It should be noted that rocks were digitized and must be removed from the data set for the APPS/APO data set. The operator repeatability exceeds 10 cm resolution.**

GRA tested APO'S data further using image coordinates measured from the APPS, the data was reduced in GRA propitiatory software. The data was reduced using computation modes set for no distortion and radial distortion. A check point was compared with its original survey value.

All data in millimeters

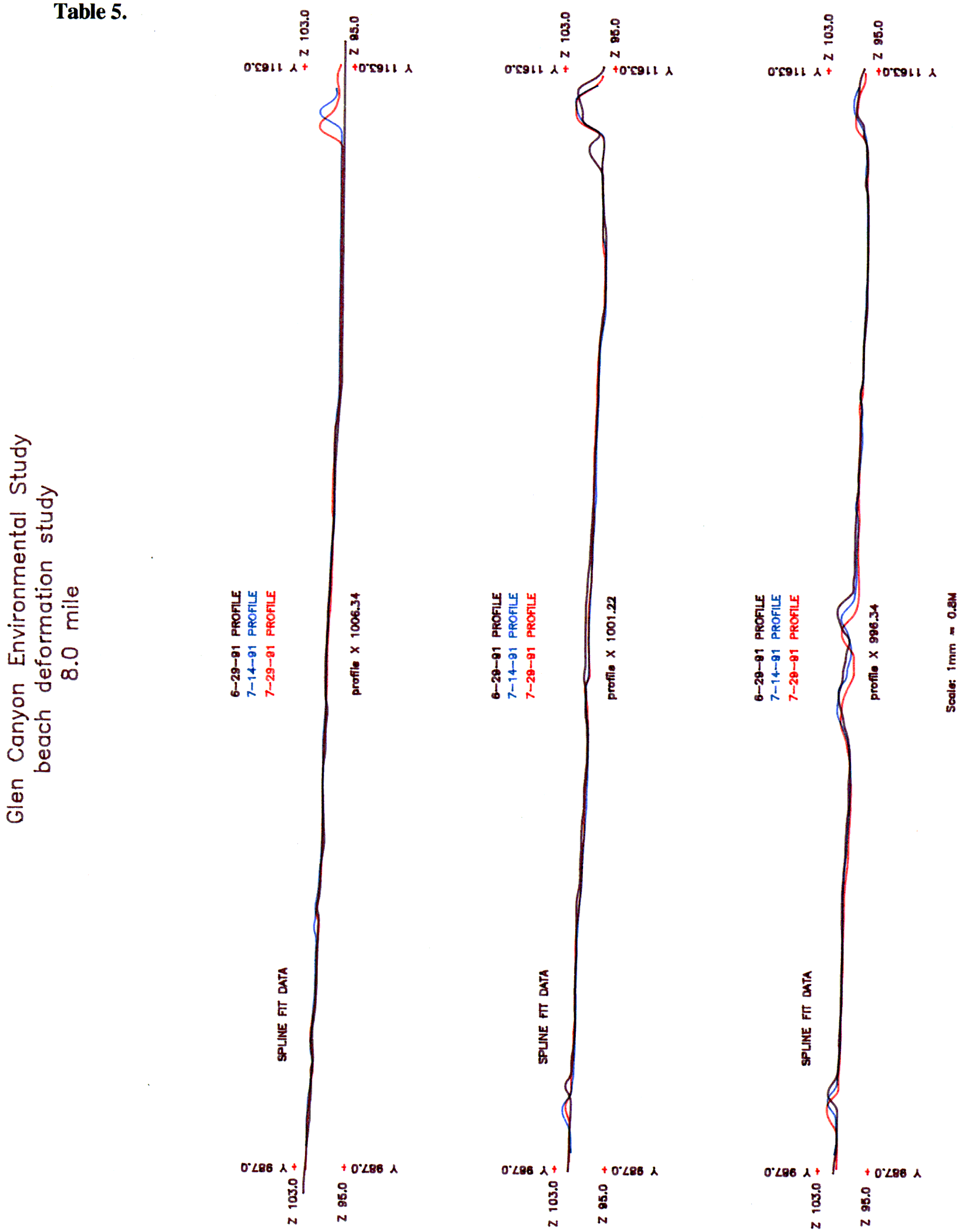
No distortion considered:

| | X | Y | Z |
|---|---|---|---|
| RMS | | | |
| | 0.015 | 0.024 | 0.071 |
| Check Point 3 | | | |
| | 0.015 | 0.080 | 0.044 |

Radial distortion considered:

| | X | Y | Z |
|---|---|---|---|
| RMS | | | |
| | 0.006 | 0.012 | 0.018 |
| Check Point 3 | | | |
| | 0.078 | 0.039 | 0.027 |

**Table 5.**



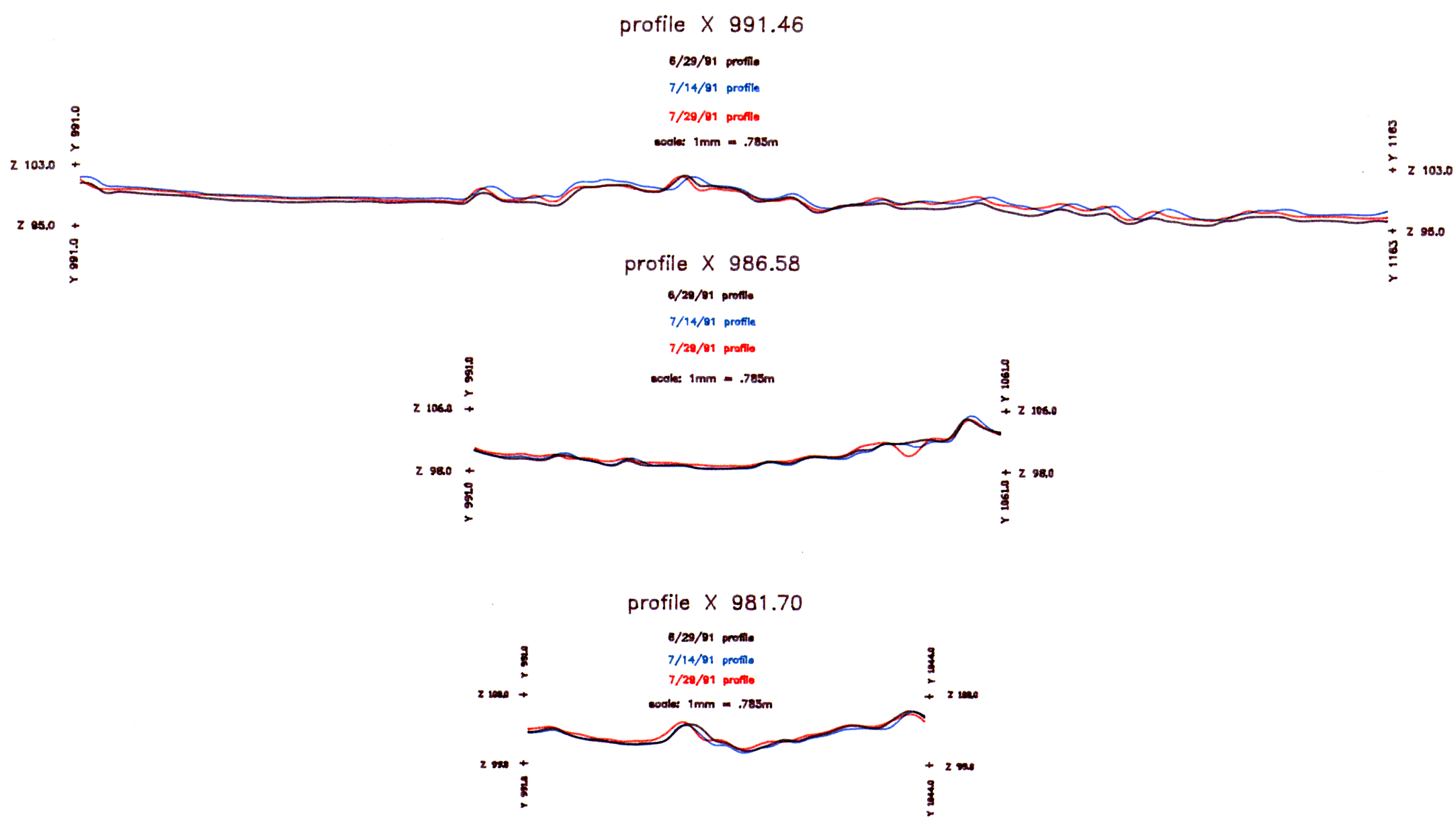
Glen Canyon Environmental Study
beach deformation study
8.0 mile
6-29-91 PROFILE
7-14-91 PROFILE
7-29-91 PROFILE
profile X 1006.34
profile X 1001.22
profile X 996.34
SPLINE FIT DATA
Z 103.0
Z 95.0
Y 1163.0
Y 987.0
Scale: 1mm = 0.8M

**Table 6.**

Glen Canyon Environmental Study

beach deformation analysis

8.0 mile



GRA initiated an additional repeatability test utilizing APO staff and the APPS IV analytical plotter. The test differences is from data collected for the 6/29/91 epoch. This data represents delta Z comparisons from a profiles duplicated on the same photographic stereo pair.

All data in millimetres:

Check Point Differences

| Point | X | Y | Z |
|---|---|---|---|
| 2 | .0000 | .0000 | .0160 |
| 3 | .0000 | .0000 | .0670 |
| 4 | .0000 | .0000 | .0440 |
| 5 | .0000 | .0000 | .0400 |
| 6 | .0000 | .0000 | .0880 |
| 7 | .0000 | .0000 | .1170 |
| 8 | .0000 | .0000 | .0830 |
| 9 | .0000 | .0000 | .0840 |
| 10 | .0000 | .0000 | .0320 |
| 11 | .0000 | .0000 | .0730 |
| 12 | .0000 | .0000 | .2040 |
| 13 | .0000 | .0000 | .0610 |
| 14 | .0000 | .0000 | .0190 |
| 15 | .0000 | .0000 | .0570 |
| 16 | .0000 | .0000 | .0130 |
| 17 | .0000 | .0000 | .0330 |
| 18 | .0000 | .0000 | .1230 |
| 19 | .0000 | .0000 | .1710 |
| 20 | .0000 | .0000 | .0560 |
| 21 | .0000 | .0000 | .1760 |
| 22 | .0000 | .0000 | .1210 |
| 23 | .0000 | .0000 | .0600 |
| 24 | .0000 | .0000 | .0130 |
| 25 | .0000 | .0000 | .0140 |
| 26 | .0000 | .0000 | .0130 |
| 27 | .0000 | .0000 | .0060 |
| 28 | .0000 | .0000 | .0410 |
| 29 | .0000 | .0000 | .1000 |
| 30 | .0000 | .0000 | .1150 |
| 31 | .0000 | .0000 | .1180 |
| 32 | .0000 | .0000 | .1190 |
| 33 | .0000 | .0000 | .2500 |
| 34 | .0000 | .0000 | .2120 |
| 35 | .0000 | .0000 | .0790 |
| 36 | .0000 | .0000 | .0340 |
| 37 | .0000 | .0000 | .0850 |
| 38 | .0000 | .0000 | .0560 |
| 39 | .0000 | .0000 | .0640 |
| 40 | .0000 | .0000 | .0270 |
| 41 | .0000 | .0000 | .1370 |
| 42 | .0000 | .0000 | .0890 |
| 43 | .0000 | .0000 | .0660 |
| 44 | .0000 | .0000 | .0220 |

| | | | |
|---|---|---|---|
| 45 | .0000 | .0000 | .0480 |
| 46 | .0000 | .0000 | .0310 |
| 47 | .0000 | .0000 | .0340 |
| 48 | .0000 | .0000 | .0600 |
| 49 | .0000 | .0000 | .1330 |
| 50 | .0000 | .0000 | .0110 |
| 51 | .0000 | .0000 | .0480 |
| 52 | .0000 | .0000 | .0190 |
| 53 | .0000 | .0000 | .0220 |
| 54 | .0000 | .0000 | .0020 |
| 55 | .0000 | .0000 | .0220 |
| 56 | .0000 | .0000 | .0150 |
| 57 | .0000 | .0000 | .0070 |
| 58 | .0000 | .0000 | .0430 |
| 59 | .0000 | .0000 | .0630 |
| 60 | .0000 | .0000 | .0810 |
| 61 | .0000 | .0000 | .1980 |
| 62 | .0000 | .0000 | .1970 |
| 63 | .0000 | .0000 | .2320 |
| 64 | .0000 | .0000 | .1710 |
| 65 | .0000 | .0000 | .1440 |
| 66 | .0000 | .0000 | .0780 |
| 67 | .0000 | .0000 | .0930 |
| 68 | .0000 | .0000 | .1850 |
| 69 | .0000 | .0000 | .0420 |
| 70 | .0000 | .0000 | .0010 |
| 71 | .0000 | .0000 | .0670 |
| 72 | .0000 | .0000 | .0250 |
| 73 | .0000 | .0000 | .0220 |
| 74 | .0000 | .0000 | .0130 |
| 75 | .0000 | .0000 | .1050 |
| 76 | .0000 | .0000 | .0240 |
| 77 | .0000 | .0000 | .0950 |
| 78 | .0000 | .0000 | .0260 |
| 79 | .0000 | .0000 | .0530 |
| 80 | .0000 | .0000 | .0910 |
| 81 | .0000 | .0000 | .0680 |
| 82 | .0000 | .0000 | .0030 |
| 83 | .0000 | .0000 | .0490 |
| 84 | .0000 | .0000 | .0470 |
| 85 | .0000 | .0000 | .0130 |
| 86 | .0000 | .0000 | .0360 |
| 87 | .0000 | .0000 | .0210 |
| 88 | .0000 | .0000 | .2520 |
| 89 | .0000 | .0000 | .2890 |
| 90 | .0000 | .0000 | .1920 |
| 91 | .0000 | .0000 | .2550 |
| 92 | .0000 | .0000 | .1140 |
| 93 | .0000 | .0000 | .0600 |
| 94 | .0000 | .0000 | .1170 |
| 95 | .0000 | .0000 | .0000 |
| 96 | .0000 | .0000 | .1050 |
| 97 | .0000 | .0000 | .0870 |
| 98 | .0000 | .0000 | .0820 |

| | | | |
|---|---|---|---|
| 99 | .0000 | .0000 | .0690 |
| 100 | .0000 | .0000 | .0450 |
| 101 | .0000 | .0000 | .0820 |
| 102 | .0000 | .0000 | .0150 |
| 103 | .0000 | .0000 | .0390 |
| 104 | .0000 | .0000 | .0210 |
| 105 | .0000 | .0000 | .0790 |
| 106 | .0000 | .0000 | .0060 |
| 107 | .0000 | .0000 | .0040 |
| 108 | .0000 | .0000 | .1350 |
| 109 | .0000 | .0000 | .0810 |
| 110 | .0000 | .0000 | .0850 |
| 111 | .0000 | .0000 | .0250 |
| 112 | .0000 | .0000 | .0470 |
| 113 | .0000 | .0000 | .1150 |
| 114 | .0000 | .0000 | .1160 |
| 115 | .0000 | .0000 | .1170 |
| 116 | .0000 | .0000 | .1110 |
| 117 | .0000 | .0000 | .0730 |
| 118 | .0000 | .0000 | .1490 |
| 119 | .0000 | .0000 | .1330 |
| 120 | .0000 | .0000 | .0560 |
| 121 | .0000 | .0000 | .0260 |
| 122 | .0000 | .0000 | .0640 |
| 123 | .0000 | .0000 | .0340 |
| 124 | .0000 | .0000 | .0060 |
| 125 | .0000 | .0000 | .0370 |
| 126 | .0000 | .0000 | .0100 |
| 127 | .0000 | .0000 | .1830 |
| 128 | .0000 | .0000 | .2640 |
| 129 | .0000 | .0000 | .2550 |
| 130 | .0000 | .0000 | .1730 |
| 131 | .0000 | .0000 | .1430 |

NOTE: The profile difference does not compare with any of the other test's undertaken. The photography, survey control and the ability to accurately measure the models have been proven beyond a doubt. The ONLY reasons for this difference can be explained by the following.

1- The second and third data sets were not measured under the original supervised conditions.

2- The stereo models were not set up properly (parallax errors) and the solution was ill constrained.

3- lack of attention to detail by the stereo plotter operator.

4- lack of acute stereo vision by the operator.

## 6.0 Conclusion and Recommendations:

### 6.1 Initial Comments:

The overall results as far as data output and expenditure of time on the GCES environmental study has been very poor. In general there has been a lack of attention to detail and overall lack of management follow up regarding this project.

After the initial meetings APO/GCES in August of 1990 APO photographed the September 16 epoch. The photography had poor geometry and image motion was apparent in some of the images.

The majority of the beaches had no survey control targets, and up to January of 1991 there was no decision as to what beaches would be photogrammetricaly mapped.

The research flows had started when the discussions were held on the use of photogrammetry. There was no pre planning as to placement of control or what beaches would be used for the photogrammetric study.

The GCES study was a high profile project in that the data from the study would be disputed and litigation was probable. GRA was called to support APO/GCES based on their twelve years experience of helicopter based geotechnical mapping and their strong international experience on high profile and litigation projects.

Normally GRA is responsible for the entire photogrammetric process in this case we were to assist in the photography phase only with no control of the survey or final mapping. This would nullify our input in any litigation matters concerning mapping in the Grand Canyon.

From October to December photography of the beaches were undertaken with no control targets. The process of transferring control from post photography to pre photography is an expensive process with more chances of error.

In December a survey team was sent down the Canyon by raft. Their task was to place removable control targets on the beaches, survey the targets and natural features required for the photogrammetric mapping. The schedule was very aggressive and near impossible to meet. Gary Robertson from GRA spent the first day on the survey, he found that the survey procedures were in error and instructed the team on the proper procedure to be used. The initial schedule showed that three beaches were to be surveyed per day. That first day only 50 percent of the survey of one beach was completed.

The following day APO was informed of the findings by GRA, and reported that the survey procedures were poor and could affect the overall project. It was later found that GCES survey team disregarded the procedures that GRA had requested based on time constraints. The survey control panels were not distributed in an optimum layout on every beach due to untrained personel on some of the sites.

I would like to point out at this time that the survey control might prove to be within the described accuracy limits on some beaches. The procedures used to gather the control was WRONG and would be unacepptable in any dispute or court litigation.

In addition there was no contract in place for APO/GCES to have GRA or other contractor's check the data. Nearly three months had elapsed before any serious attempts were made to map the beaches. It was not until January that the specific beaches were selected for mapping.

Photogrammetric mapping of selected beaches was attempted, and discovered that there were control problems, poor target geometry, and poor base distance geometry of the photography. In addition it was discovered that altimeter errors occurred during the flights and airspeeds exceeded 40 mph creating image motion problems.

### 6.2 Final Recommendations:

The test of 8.0 mile beach shows that photogrammetry can provide the desired accuracies on the GCES study beaches. The following are quide lines for the future successful mapping of the GCES study beaches and comments on the use of available photography of the beaches.

#### 6.2.1 Administrative:

1: The selection of qualified team members for the various project phases.

2: All schedules based on feasible milestones after accurate evaluation of the team proficiency

3: Separate resolution criteria for each subject.

4: Proper project management with interim project evaluation from all primary team members

5: Insure that all contract mechanisms are in place for technical support by specialist contractors

### 6.2.2 Survey:

The need for well distributed control is necessary. The sensitive environmental nature of the Grand Canyon allows only for temporary placement of control target panels. Since the security of the targets would be in question, to be effective, one will need to use well distributed natural features. This is especially required in the areas of the fine deposits on the beaches. The use of natural features does present some problems. The documentation of the natural features has to be prepared in detail in the field with supporting photographs of the point. In addition the photogrammetric operators need to be experienced working with natural features, the survey team should be available to assist the photogrammetric operators on the initial measurement phase.

The most important criteria is that of quality surveys. This requires that proper survey procedures be undertaken, especially with redundancy of all survey data acquired. In addition it is advantageous that the beaches included in the GCES study be tied together within the same survey network. In addition qualified survey personnel must be used with proper equipment.

### 6.2.3 Photography:

Taking into consideration the previous comments on cameras, the 70 mm format camera is recommended for the photography of the beaches. Although the UMK 200 camera could be used depending on the beach dimensions.

The camera bases or the model base distance geometry is important as shown in simulation and accuracies can be achieved with a large percentage of the existing photography. Initial problems with bases can be attributed to no ground targets for reference, turbulence, altitude and airspeed problems. In addition to camera operator errors.

After analysis of most epochs we found that the film that was pushed due to overcast conditions was extremely poor and the expected accuracies would be impossible to meet. The film used was Kodak T-Max 400 ASA film. This film offered the capability of "pushing" or increasing the film speed. The photography of some beaches had film speeds of 1600, 3200, and in some cases 6400. The decision to photograph some of the beaches under poor light conditions was a sound one. Since the research flows were only during the weekend period and each flow was at a cost of $250,000, a decision was made that it would be better to at least get a record of the beach, rather than no record at all. The aggressive schedule with poor weather and short winter days made the lighting conditions less than ideal.

Shadows on the beach presented fewer problems than overcast conditions or late afternoon days.

All film was processed immediately after the flights, and checked for coverage. There would be no advantage to processing the film on site since the research flows were limited and in most cases not allow for additional photography.

### 6.2.4 Helicopter and other logistics

Due to the length of the Canyon and the time frame, the helicopter procedures used were very good. The photography would start at the upstream portion at Page and continue to Tusayan for refueling. If a portion of beach is under heavy shadow or in overcast conditions the distances made it very difficult for the helicopter to return and photograph the site.

The APO Bell Long Ranger helicopter offers and excellent camera platform. The Bell 206 helicopter also can be used but with the extra room and the stable flight characteristics of the Long Ranger makes it a better choice.

The APO flight department operates two Long Ranger helicopters with experienced pilots and many years of Grand Canyon flying experience. It would be a major advantage to use these resources at APO for any future photogrammetric work.

### 6.2.5 Safety

The overall safety of helicopter photography has been excellent. In over twelve years of helicopter photography we have had only one serious accident, and the last ten years has been accident free. In addition all photogrammetric team members must be experienced in working out of helicopters.

We have at this time no data on the safety record of the ground survey in the canyon. This survey utilizes rafts and no data was available as to injuries or major equipment loss or damage.

### 6.2.6 Photogrammetric Mapping

The photogrammetric mapping of the beaches should be produced utilizing modern first order instruments. The Government support agencies at APO and USGS\Flagstaff are equipped with old obsolete stereo plotters. The instruments at APO are less than 10 micron instruments, but acceptable mapping can be made with these instruments under certain mapping scales and accuracies. Where these instruments fail is in the optics and illumination system which at high magnification makes measuring the fine deposits on the beaches near impossible. In addition APO stereo plotter operators seem to lack knowledge on proper model setups that include weighting principals and orientation procedures.

Utilizing accurate photo control and good image geometry, the mapping of the beaches could be completed within three weeks after photography. This would be based on mapping of 20 beaches and the use of one instrument.

Several types of products can be produced from the digital data including profiles, DTM models or contour maps. To best illustrate the beach loss I would suggest profiles versus producing contour maps. In addition DTM models of the beach could be prepared with the same viewpoint and rendered, this could be later presented by animation techniques for video tape or film. This animation procedure could be used on beaches with the largest erosion displacements.

The raw data output should be translated to straight ASCII format as to allow other groups and agencies to work with the data .

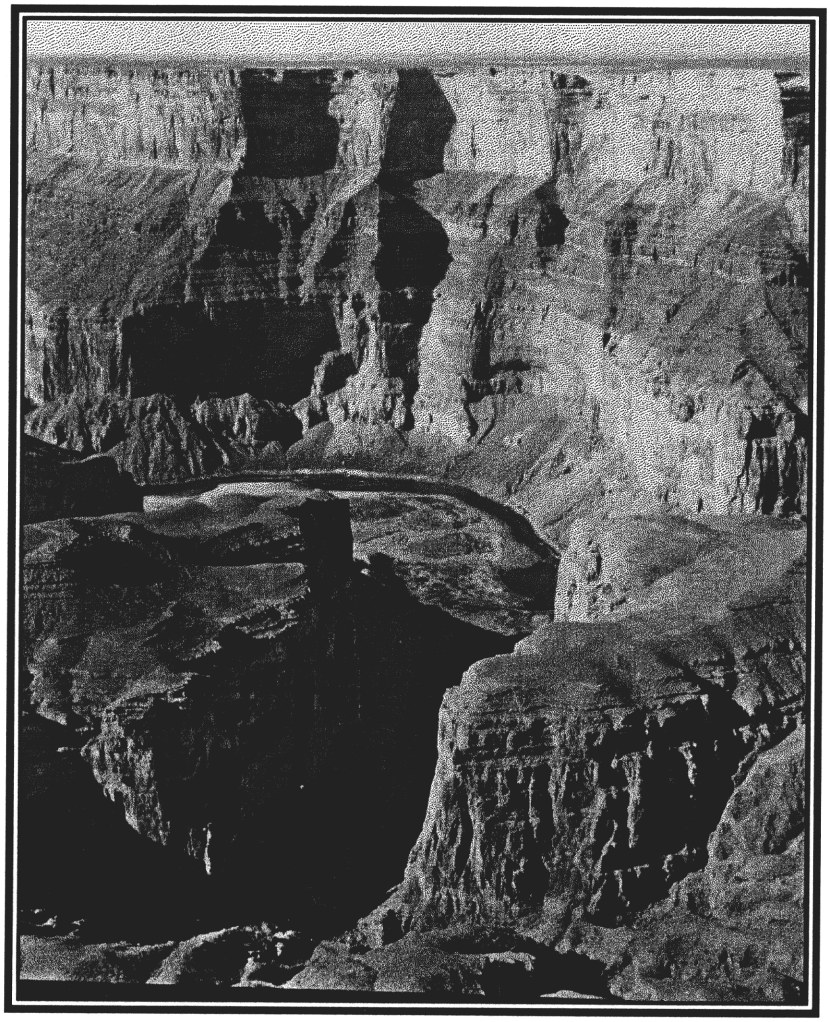
The mapping accuracies of some beaches can be decreased based on the amount of displacement on the beaches. The existing photography can be used under the following conditions:

1- The beaches are surveyed and natural targets selected

2- The mapping accuracies be decreased to allow for images with a large amount of erosion, lighting and poor image geometry.

Photogrammetric mapping procedures used on this project have been used in several countries with great success. Major projects requiring tens of thousands of stereo pairs utilizing helicopters have been measured with success.

The photogrammetric procedure is the only practical procedure that can be used to map the fine deposits on the designated number of Grand Canyon beaches. If the procedure outlined in this report are followed acceptable mapping accuracies can be achieved in a timely matter.



## APPENDIX A

The following are prints of the 8.0 mile test beach to illustrate the scale and overall coverage.